NASA's Tropical Cloud Systems and Processes (TCSP) Experiment: Investigating Tropical Cyclogenesis and Hurricane Intensity Change

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Abstract

In July, 2005 the National Aeronautics and Space Administration (NASA) investigated tropical cyclogenesis, hurricane structure and intensity change in the eastern Pacific and western Atlantic using its ER-2 high altitude research aircraft. The campaign, called the Tropical Cloud Systems and Processes (TCSP) experiment, was conducted in conjunction with the National Oceanographic and Atmospheric Administration (NOAA) Hurricane Research Division (HRD) Intensity Forecasting Experiment (IFEX). A number of *in situ* and remote sensor datasets were collected inside and above four tropical cyclones (Hurricanes Dennis and Emily, Tropical Storm Gert and the pre-genesis stages of Tropical Storm Eugene). These four storms represent a broad spectrum of tropical cyclone intensity and development in diverse environments. While the TCSP datasets directly address several key hypotheses governing tropical cyclone formation, the campaign also sampled two unusually strong, early season storms. Highlights from the genesis missions are described in this article, along with some of the surprises and unexpected results from the campaign.

The manner in which tropical disturbances quickly develop into depressions, storms or hurricanes (termed tropical cyclogenesis) remains one of the outstanding and fascinating research topics in meteorology. Hurricanes are the greatest natural disasters facing coastal regions of the United States. While predictions of hurricane track and point of landfall have steadily improved over the past several decades, progress in improving intensity change forecasts remains slow. During July, 2005, the National Aeronautics and Space Administration (NASA) conducted its Tropical Cloud Systems and Processes (TCSP) experiment from San Jose, Costa Rica. The purpose of TCSP was to investigate the genesis and intensification of tropical cyclones primarily in the eastern Pacific. This ocean basin was chosen because it represents the most concentrated region of cyclone formation on the planet, and is within range of research aircraft deploying from Costa Rica. Twelve separate missions were flown by the NASA ER-2 high altitude research aircraft, carrying a payload of *in situ* and remote sensing instrumentation. Many of these missions were flown in coordination with the NOAA Hurricane Research Division (HRD) P-3 Orion research aircraft as part of NOAA's 2005 Intensity Forecast Experiment (IFEX - described in a companion article in this issue of the *Bulletin*).

TCSP leverages off of a series of NASA field programs investigating tropical cyclones, beginning with the Third Convection and Moisture Experiment (CAMEX-3) in 1998 and continuing with CAMEX-4 in 2001 (Kakar et al., 2006). TCSP's successor program, the NAMMA-06 (NASA African Monsoon Multidisciplinary Activities) experiment, is planned for September, 2006. A mandate of the NASA Weather Focus Area is to investigate high impact weather events, such as severe tropical storms, through a combination of new and improved space-based observations, high-altitude research aircraft and sophisticated numerical models to improve the understanding and predictability of weather, climate and natural hazards. The TCSP campaign, as well as the earlier CAMEX programs, are vital components of this three-pronged approach. The strategy enables scientists to better understand the physics of tropical cyclones, improve model parameterizations and methods to assimilate diverse datasets, and provides a test-bed for new observing technologies such as Uninhabited Aerial Vehicles (UAVs), on-board processing of information, and high-altitude dropwindsondes.

(1) Scientific Objectives

The TCSP science team, which includes the diverse group of government and academic scientists listed in Table 1, collected data on the multi-scale interaction of thermodynamic and dynamical processes governing the early evolution of tropical cyclones, ranging from the microphysical scale through the synoptic scale. TCSP science embodies a synergistic blend of aircraft measurements, satellite measurements such as the Tropical Rainfall Measurement Mission (TRMM), and high resolution numerical models such as the Weather Research and Forecasting (WRF) model. TCSP research broadly addresses the following overarching scientific themes: 1) tropical cyclogenesis, structure, intensity change, moisture fields and rainfall distribution; 2) satellite and aircraft remote sensor data assimilation and validation studies pertaining to tropical cyclone development; and 3) the role of upper tropospheric/lower stratospheric processes governing tropical cyclone outflow, the response of wave disturbances to deep convection and the evolution of the upper level warm anomaly. Following are some key questions related to tropical cyclone genesis and intensity change that are being examined:

- What processes govern genesis in the eastern Pacific and Caribbean: Intensification of traveling easterly waves into depressions, regional generation of cyclonic vorticity, or some combination of both?

- What dynamical and thermodynamic processes involving both the atmosphere and upper ocean contribute to rapid intensification of tropical cyclones, including the frequent occurrence of convective bursts during the development stage?

- How does the low-level vortex of a tropical cyclone become established, including processes related to the descent of mid-level mesoscale vortices, the generation of convective-scale vortical hot towers and the horizontal merger of vortices?

Additionally, during periods of inactive tropical cyclone development, TCSP research was focused on obtaining detailed observations of organized deep convective systems in various geographical settings, and flying calibration-validation underpasses of NASA satellites as orbits of opportunity arose.

(2) Practical Significance of TCSP Research

TCSP scientists are sometimes asked why it is important to study storm formation in the tropical Pacific, since these storms rarely affect the United States. First, the processes by which tropical waves become depressions, storms, and then hurricanes are fundamentally similar in all oceans. Although some details may differ, the similarities offer clues that aid understanding. Second, better understanding of these processes extends the time range of skillful forecasts of hurricanes and saves lives and property.

The 2005 hurricane season showed the importance of extending the time of accurate forecasts. Evacuations take time. They disrupt individuals and are costly to communities, to business, and to governments. They can also be dangerous. The decision by public officials to issue large-scale evacuation orders, or by individuals to abandon their homes, is never an easy one. Despite improvements in hurricane track forecasting, intensity change forecasts have not kept pace. In August 2005, a tropical depression in the Bahamas intensified rapidly enough to strike the Miami area as a hurricane (Katrina) in less than 42 hours. While forecasts and warnings were good for this case, they would not have given sufficient lead time if the scenario had been slightly different. For example, evacuation of the Florida Keys requires up to 72 hours, depending upon the anticipated wind speed and storm surge. Wilma (2005) intensified at an amazing rate, with the central pressure dropping 62 hPa in 7 hours. Forecasters as well as those making evacuation decisions understandably may err on the side of caution when looking at the history of 2005.

At the same time, no one wants evacuations that prove to be less than absolutely necessary. They are expensive and sometimes tragic as in the case of the 24 lives lost during the evacuation of the Houston area for Rita 2005. So increasing the lead time and accuracy of intensity forecasts is important not only for adequate warning time for a threat that materializes, but to avoid evacuations that will later be viewed as false alarms. Ironically, the improved accuracy of hurricane track forecasting has increased the need for better intensity forecasts. This is because more sophisticated numerical models sometimes intensify weak disturbances into hurricanes over a 72-hour period, which we know is a possibility, and show a forecast track that may be accurate. It may be only a matter of time before decision-makers will face the dilemma of whether to begin an evacuation in advance of a storm "threatening" a vulnerable coastal area before the storm has been named.

The tropical oceans are filled with disturbances throughout the storm season, but only some of them will eventually be named as tropical storms. Forecasting the intensity change of storms that are already intense is of obvious practical importance. But so is anticipating which weak disturbances will remain only rainstorms, and which bear close watching for rapid intensification.

(3) Resources and Strategies in the Field

The NASA ER-2 high altitude research aircraft served as the primary platform for collecting a variety of remotely sensed data on the genesis, intensification and decay of several Atlantic and eastern Pacific tropical disturbances. The ER-2 aircraft flew approximately 85 flight hours divided among 12 missions, including sorties flown above Tropical Storm Gert, the precursor to Tropical Storm Eugene, and Hurricanes Dennis and Emily. Table 2 presents a synopsis of these missions. Detailed information about the TCSP campaign, daily mission summaries, satellite animations, flight tracks and quicklook images of the data can be found by visiting the TCSP website at http://tcsp.nsstc.nasa.gov.

TCSP missions were planned and executed in conjunction with the NOAA Hurricane Research Division P-3 Orion research aircraft. The advantages of such a collaboration are two-fold: (a) the NASA ER-2 flies high (over the storms) and the NOAA P-3 flies low (around and through the storms), ensuring near-complete vertical coverage of the tropical cyclone from 21 km in the atmosphere downward through the planetary boundary layer and oceanic mixed layer; and (b) the experience and knowledge of each agency are combined to effectively address unresolved critical issues surrounding genesis of tropical cyclones and their rapid intensification. For instance, during TCSP the NASA ER-2 and NOAA P-3 were able to fly a total of five back-to-back missions to obtain continuous coverage during the pre-genesis phases of Tropical Storm Eugene. Additionally, for the first time, the complete lifecycle of a tropical cyclone (Gert) was captured from its genesis off the Yucatan Peninsula to landfall and dissipation over the mountains of Mexico.

Figure 1 shows the instrumentation that was carried on board the ER-2. In addition to the ER-2, NASA operated Aerosonde UAVs on eight missions to sample the eastern Pacific boundary layer during both pre-genesis and inactive phases of TCSP. NASA also deployed six-hourly GPS radiosondes from Juan Santamaria International Airport to support scientific and aircraft operations, including validation of NASA's Aura satellite.

Collaboration with Costa Rican scientists, students and officials from the Ministry of Science and Technology were essential to the success of the TCSP campaign. Scientists from the University of Costa Rica (UCR) and local forecasters provided valuable insight into regional cloud and rainfall patterns influenced by the complex terrain surrounding San Jose and the adjoining Pacific Ocean. The frequent occurrence of nocturnal fog and low visibility stratiform rain proved very challenging for ER-2 operations into and out of the airfield. The UCR students participated in the preparation of daily forecasts and radiosonde launches. Scientists from both UCR and the Costa Rican Center for Advanced Technology are working with U.S. colleagues to begin synthesizing the diverse datasets collected during TCSP.

The TCSP field campaign benefited from a wealth of available real-time satellite imagery and products. Most of this data was accessible by the mission planners in Costa Rica, either by direct access on site, or by remotely accessed web sites. The principle satellites of interest to TCSP field support and research are NASA research satellites such as TRMM, Aqua, Terra, and QuikSCAT and operational satellites such as NOAA GOES-11 (geostationary, operating in rapid-scan imaging mode at five-minute intervals) and NOAA and Defense Meteorological Space Package polar orbiters. All routinely available data from these satellites were archived, and are available from the TCSP data management web site.

The field phase of TCSP required daily preparation of weather briefings, both to support aircraft operations and to develop scientific strategies for flying meteorological targets of interest. Teams of students from Florida State University, Colorado State University, Ohio State University, University of Costa Rica and Texas A&M provided this support. Their forecasts included products from the National Weather Service, United States Navy, National Hurricane Center, Costa Rican Meteorological Service, and the Florida State University superensemble model. Tropical cyclones Dennis, Emily, Eugene and Gert provided a unique opportunity for mesoscale modeling of genesis and intensity changes. To provide insight for TCSP objectives, aircraft and very high resolution satellite measurements of surface winds (i.e. QuikSCAT), precipitation and microphysical parameters will be assimilated into the models for sensitivity studies of various physical processes.

The TCSP mission planning and monitoring were aided by real-time and near-real time imagery posted to TCSP web sites. The ER-2 flight tracks, aircraft electric field and ground-based lightning network information were displayed along with GOES imagery in real-time on the TCSP web site. Telemetry of the ER-2 information was facilitated by the Research Environment for Vehicle-Embedded Analysis on Linux (REVEAL) system developed at the NASA Dryden Flight Research Center. The REVEAL system, which is a flexible sensor acquisition and processing system, provided the TCSP science team with over-the-horizon mission monitoring capabilities throughout the flight. Satellite imagery and products were also made available through sites located at the University of Wisconsin – Cooperative Institute for Meteorological Satellite Studies (UW-CIMSS), and the Naval Research Laboratory at Monterey (NRL-Monterey). Real time imagery and derived products were made available to the TCSP project during the entire month of July 2005. The imagery/products included larger-scale domains, and focused zooms over the area of TCSP mission interest. The web sites can be found at: NRL-Monterey http://www.nrlmry.navy.mil/tc_pages/tc_home.html (Select Year 2005 and view Eastern Pacific (EPAC) systems with TCSP in the storm name), and UW-CIMSS http://cimss.ssec.wisc.edu/tropic/tcsp

Aircraft mission planning was greatly facilitated by special tasking of the NOAA GOES-11 satellite in rapid scan mode over Central America. Data from the Costa Rican regional lightning detection network were routinely overlaid on the satellite imagery to help identify the most vigorous convective cores. TCSP mission scientists could monitor the real time progress of the ER-2 aircraft by noting its current position and track in relation to these high resolution cloud and lightning features.

All of the satellite data collected in real time are available for post analysis on these two sites. Examples of derived products of special interest to the TCSP campaign include high-density cloud-motion winds derived at CIMSS on an hourly basis from the GOES-11 five-minute rapid scan imagery. An example of this product can be found at the UW-CIMSS web site: http://cimss.ssec.wisc.edu/tropic/tcsp/archive/winds/18Jul2005-12z-upperwindsS.gif

The TCSP field campaign will in turn offer opportunities for satellite data validation and numerical model forecast impact experiments. Several investigators plan satellite data assimilation as part of a tropical cyclone genesis-modeling component of the project.

(4) Accomplishments, Surprises and Unexpected Experiences

Figure 2 illustrates a satellite mosaic of the principal storm systems into which TCSP aircraft flew, along with the track and intensity of each storm. During the typical hurricane season, the Atlantic Basin is generally quiet during the month of July. TCSP was formulated with the assumption that most of the tropical storm activity during July would be in the Eastern Pacific region as based on climatology. This motivated our choice to conduct the mission out of San Jose, Costa Rica. Such a location allows ready access to storms undergoing genesis along the west coast of Central America and

Mexico, while also allowing for sampling targets of opportunity in the Caribbean or Gulf of Mexico. During the very unusual 2005 season, there were seven Atlantic tropical storms before August 1 compared to the previous record of five in 1997. Two of these storms (Hurricane Dennis and Hurricane Emily) were Category 4 or greater and are the strongest July storms in the Atlantic Basin ever reported.

The first priority of TCSP was to investigate the development of tropical cyclones from locally generated and/or traveling wave disturbances. Fortunately, there were several targets of opportunity in the Caribbean and Eastern Pacific. The evolution of Dennis was well-sampled by ER-2 and P-3 aircraft from the tropical depression stage through maturity. Seven total aircraft missions were flown into a region of the eastern Pacific where cyclogenesis was predicted to occur; one or more of these flights likely captured the pre-genesis phase of Tropical Storm Eugene. Finally, late in July the NASA and NOAA aircraft sampled the complete life-cycle of Tropical Storm Gert, successfully capturing the transition of an easterly wave encroaching on the Yucatan Peninsula into the depression stage, tropical storm stage and subsequent landfall near Tampico, Mexico.

4a. Hurricane Dennis

During the very first week of TCSP, Tropical Storm Dennis formed in the southeast Caribbean. Three coordinated flights between the NOAA P-3s and the ER-2 were performed on 5, 6 and 9 July. These flights covered the development of Dennis from a tropical depression to a tropical storm, and later to a hurricane. During the second coordinated flight on 6 July, the NASA ER-2 and NOAA P-3 flew missions to investigate the development and intensification of Tropical Storm Dennis in the southeast Caribbean off the north coast of Venezuela. During the mission, the National Hurricane Center upgraded Tropical Storm Dennis to a Category 1 hurricane. The two aircraft not only documented the intensification of a tropical storm, but focused portions of the flights on monitoring microphysical processes in the storm's rain bands. These three coordinated flights as well as other NOAA P3 flights into Dennis sampled nearly the entire lifecycle of a hurricane during TCSP.

An example of the microphysical structure of Dennis collected by the NOAA P3 aircraft flying in the mixed phase region is shown in Figure 3. Several minutes prior to each eyewall penetration, the P3 climbed from the +5 to -3C temperature levels. In the first (northward) penetration, large snow and graupel up to 2 cm in diameter were encountered at sub-freezing temperatures in convection on the south side of the eye (Fig. 1, < 0°C), There was no isothermal (melting) layer, signifying that these regions were indeed convective. To the north of the eye, weak stratiform precipitation and relatively small raindrops were sampled. In the second, north to south penetration of the eye, weak convection was again penetrated to the north of the eye. In the eyewall just to the south of the eye, graupel particles 2 cm in diameter were again observed. The abrupt fluctuations noted in the particle size distributions to the south of the eye are clear indications of rainband penetrations. The penetrations through the eye, at a temperature of +5C, were free of cloud.

4b. Hurricane Emily

Another surprise during TCSP was the development of strong category Emily in the same region where Dennis initially formed. The first mission to study Emily was on 17 July when it was already a Category 4 storm. As Emily moved toward the Yucatan peninsula and the Texas-Mexico border, TCSP scientists decided to fly only the ER-2 for the mission since NOAA HRD staff were anticipating the operational tasking of the P3s.

The objective of the Hurricane Emily flight was to document the convective structure of an intense hurricane. Detailed measurements of the eyewall were the main objective, with sampling of intense convection in outer rainbands the secondary objective. The ER-2 overflew Hurricane Emily in the early morning hours of 17 July as the storm passed between Honduras and the Cayman Islands. Prior to the ER-2 launch, Air Force reconnaissance recorded a deepening from 953 hPa at 0541 UTC 16 July, to 946 hPa at 1152 UTC, thence to 929 hPa at 2340 UTC. The last Air Force fixes of the night showed rapid filling to 943 hPa by 0534 UTC 17 July.

During the very first eye crossing (ESE-WNW) by the ER-2, the pilot encountered strong turbulence (Fig. 4c,e). Data collected by the ER-2 Doppler Radar (EDOP) and Airborne Microwave Precipitation Radiometer (AMPR) instruments during this flight (Fig. 4-c,e) showed a compact eye about 30 km across with the most impressive evidence thus far of intense convection in the eyewall of a hurricane. This convection extended up to nearly 17 km altitude with unusually high reflectivities at high altitudes (~40 dBZ to ~15 km).

AMPR and HAMSR showed low brightness temperatures indicative of precipitation-sized ice. The AMPR Precipitation Index (API; Fig. 4c) merges information content from four frequencies of brightness temperatures into an indicator of precipitation ice and water. Note the purple shades of the API around the hurricane eye denoting ice scattering in three frequencies - suggesting large or graupel-sized ice particles. The LIP instrument detected very strong electrical activity during this pass (Figs. 4b, d). The maximum electric field is around 9 kV/m, one of the highest fields ever measured at ER-2 altitude. (See Hood *et al.* 2006 for a discussion of the AMPR, LIP and the API). The GOES brightness temperature (Fig. 4a) suggests a very intense isolated cell within Emily's eyewall. After two passes across the eye, the ER-2 pilot judged it unsafe to continue the planned pattern. This was the first time that hurricane convection had caused a safety concern for the ER-2 pilot at ~20 km altitude. A backup plan was quickly formulated, executing a box-type pattern just outside the eyewall. This allowed continued mapping of the inner core. A movie loop of the ER-2 aircraft track superimposed over GOES-11 infrared images and lightning network data is available at the TCSP website.

Intense thunderstorms in the eyewalls of mature hurricanes are infrequent and their role in hurricane dynamics is still uncertain. Recent research from the TRMM satellite suggests that extremely deep eyewall clouds are associated with a 70% likelihood of intensification (Kelley et al., 2004). While TRMM has sampled similar cases of intense thunderstorms in Category 4 and 5 hurricanes, this is the first time that we have been able to obtain highly detailed, close-up measurements of such a storm from the ER-2.

4c. Tropical Storm Eugene

From July 14-16, TCSP forecasters and scientists pondered numerical model guidance and analyses that suggested a heightened potential for genesis in the Eastern Pacific. Back-to-back missions were flown by the NASA and NOAA aircraft, surveying mesoscale convective systems within the Intertropical Convergence Zone (ITCZ) west of Central America. On numerous occasions, mid-level mesovortices and associated deep convection were identified through analysis of dropsondes, Doppler radar and flight level winds. Ongoing analyses of satellite, piloted aircraft and Aerosonde data - in combination with numerical modeling efforts - will reveal if one or more of these vortices and attendant convective systems served as the precursor to Tropical Storm Eugene. Eugene emerged on the northern edge of the pre-genesis region (beyond the operating range of TCSP aircraft) within a day of the survey flights.

4d. Tropical Storm Gert

Five missions were flown into Tropical Storm Gert during its lifecycle, commencing when the storm was just an open wave near the Yucatan Peninsula until landfall as a tropical storm. Early on July 23 (Fig. 5a), the NASA ER-2 and NOAA P-3 flew coordinated missions in the vicinity of intense convection east of the Yucatan Peninsula and then sampled the structure of the easterly wave along the northern coast of the peninsula. A second P-3 flight was conducted in the latter half of July 23 and surveyed the easterly wave as it moved west of the peninsula and transitioned into a depression (Figure 5b). During this period, convection was weak and scattered in the region. Early on July 24, intense convection redeveloped over the Gulf of Mexico in association with the depression (Figure 5c). Coordinated flights of the ER-2 and P-3 characterized the wind and precipitation structure of the depression as it strengthened into a tropical storm. Portions of the mission were focused on sampling the rapidly intensifying convection to determine the role of convective bursts the genesis process. A solo P-3 flight continued to investigate Gert as the storm neared the coast of Mexico late on July 24 and then a solo ER-2 flight sampled the landfall of Gert on the 25th.

Among the questions that arise from the large scale analyses and satellite data for this case are: (i) the influence of Central American orography on the wave structure and convection; (ii) the factors that determine where within the wave the depression and storm develop; and (iii) the relative influences of multiple scales, from the synoptic scale down to the convective scale, on the location and timing of tropical cyclogenesis. In order to address these questions, extensive analysis of all of the airborne observations must be conducted. However, because the airborne observations are limited in both space and time, these data must be complemented by information from other sources, including operational (GOES) and research (TRMM, Aqua, QuikSCAT) satellites as well as simulations from high-resolution numerical models such as HWRF. For example, the TRMM satellite passed almost directly over Gert at the time of cyclogenesis, providing an excellent mapping of the rainfall rates (Fig. 6a) and vertical reflectivity profiles at this crucial time. A high-resolution simulation of Gert using the WRF model reproduces many aspects of the precipitation structure (Fig. 6b) of the storm when compared to the TRMM data and generates a strong low-level cyclonic circulation. Thus, by combining information from the airborne platforms, satellites, and models, the entire life cycle of Tropical storm Gert on the synoptic, meso- and convective scales can be described in unprecedented detail.

(5) Summary and Promising Areas of Future Research

The NASA TCSP experiment was one of a comprehensive suite of campaigns investigating Atlantic tropical cyclones in 2005, which also include the NOAA IFEX conducted during July-Novembeer and the National Science Foundation-sponsored Rainband and Intensity Change Experiment (RAINEX) missions during August-September. The four storms investigated during TCSP sampled a broad spectrum of tropical cyclone evolution in the Americas, ranging from transition of an easterly wave into a depression, a pre-genesis scenario occurring within the ITCZ, the mature stage of an unusually intense hurricane, and landfall/dissipation. The TCSP datasets, analyses and numerical investigations promise to yield new insights into several vexing questions surrounding tropical cyclone genesis. The three U.S. agency-sponsored field campaigns of 2005 also attest to the vigorous scientific interest surrounding the behavior of severe tropical storms and the threat they pose to property and citizens. The TCSP datasets should improve parameterizations of physical processes contained in the predictive models, with the priority going toward advancing lead time and forecast skill of hurricane intensity change. TCSP also explored the utility of promising new technologies, such as the Aerosonde UAV, for providing long endurance monitoring of potential tropical cyclone environments. The information obtained about atmospheric boundary layer properties over large fetches of otherwise inaccessible ocean can help fill a critical data void in the initialization of hurricane forecast models.

The TCSP experiment probed some of the mysteries of tropical cyclone formation over the western side of the Atlantic basin, including modulation of easterly waves by the steep orography of the Central American cordillera. However, the relative importance of regional-scale and land-ocean processes - versus what may be a more universal set of thermodynamic and dynamical interactions on the meso- and convective scales functioning in all locations - remains to be determined. Additional aircraft-based field experiments are needed in physiographically diverse locales to help answer this crucial question. In the fall of 2006, NASA is planning a follow-on experiment investigating tropical cyclogenesis over the eastern and central Atlantic, e.g. the planned NAMMA-06 campaign. The experiment will focus on transition of African easterly waves into tropical depressions and storms in the vicinity of the Cape Verde Islands, and will also investigate the role of the Saharan Air Layer on the genesis process. The aerosols and their attendant dry airmass, stable layer and enhanced vertical shear are all hypothesized to inhibit tropical cyclone growth. When taken together, TCSP and NAMMA-06 should be able to help ascertain the importance of strongly contrasting regional atmospheric influences on both ends of the Atlantic basin, in relation to a core set of genesis processes (such as vortex merger and convective bursts) that are now being identified.

(6) Acknowledgements

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(8) Table and Figure Captions

Table 1. Name and affiliation of the TCSP Science Team members.

Table 2. Synopsis of missions flown during TCSP involving both the ER-2 and NOAA P3 research aircraft. MCS = Mesoscale Convective System.

Figure 1. Scientific instrumentation flown on board the NASA ER-2 aircraft during TCSP.

Figure 2. Satellite mosaic showing the principal storms investigated by NASA and NOAA aircraft during TCSP. Track and intensity for each storm are also shown.

Figure 3: Particle size distribution measurements during two NOAA P3 penetrations through the eye of Hurricane Dennis. The hurricane symbols show the locations of the eye. The color-coding shows representations of the particle size distributions, with an

average size distribution plotted over 5-sec intervals along the time (abscissa) axis. Concentrations are color-coded as a function of diameter (ordinate) according to color chart shown.

Figure 4. Pass across the eyewall of Hurricane Emily on 17 July 2005. Shown are a) enhanced IR GOES image with ER-2 flight track, b) LIP component electric field products, c) AMPR API product, d) LIP vector electric field, and e) EDOP reflectivity cross section. Panels (b), (d), and (e) are NW to SE time plots with time decreasing toward the right. For b) the components of the electric field are in aircraft coordinates (Ex =nose to tail, Ey = wing to wing, Ez = up to down). The various discontinuities in the fields are due to lightning flashes in the eyewall. For (c) darker shades of green indicate increasing rain rates with some precipitation ice aloft, while orange, red, and purple shades indicate increasingly large / abundant ice due to scattering in AMPR's lower frequency channels. For (d) the horizontal line is the aircraft track at altitude (nominally, 20 km); green barbs are a representation of the vector electric field along the aircraft track. The length of the barbs is proportional to the magnitude of the electric field while the angle of the barb represents the direction of the electric field.

Figure 5. The 1000 hPa winds from NCEP global analyses show the broad scale wave clearly at 0000 UTC 23 July (panel a) as well as two primary regions of convection on each side of the Yucatan peninsula. The only circulation center is found east of the peninsula. By 1200 UTC 23 July (panel b), two distinct circulation centers are present. The eastern center has fallen well behind the wave axis and subsequently weakens. The

second circulation center is near the wave axis in the far southern Gulf of Mexico and is also associated with active but not widespread convection. This is the region in which Gert formed. These two images show the complexity that arises as the wave crosses from water to land and back to water. The final image (0000 UTC 24 July, panel c) shows that only one circulation center remains, in the southwestern Gulf, with significant convection occurring within it. Vorticity fields from the NCEP analyses confirm that the center is broad and, like the convection, not clearly focused. The 12 hours before and after this time are most interesting for the diagnosis of how this storm forms within the easterly wave.

Figure 6. A comparison of satellite remotely sensed rainfall and that from a numerical model simulation of Gert. (a) TRMM derived rainfall rates at 1435 UTC 24 July and (b) simulated radar reflectivity and winds at 0.5 km at 1400 UTC from a 2-km grid scale simulation using the WRF model.

Table 1   TCSP Science Team members

Name	Affiliation
Richard Blakeslee	NASA Marshall Space Flight Center
Mark Bourassa	Florida State University
Scott Braun	NASA Goddard Space Flight Center
Daniel Cecil	University of Alabama in Huntsville
William Frank	Pennsylvania State University
Paul Ginoux	NOAA Geophysical Fluid Dynamics Laboratory
Michael Goodman	NASA Marshall Space Flight Center
Gerald Heymsfield	NASA Goddard Space Flight Center
Robbie Hood	NASA Marshall Space Flight Center
Tiruvalam Krishnamurti	Florida State University
Bjorn Lambrigtsen	Jet Propulsion Laboratory
Guosheng Liu	Florida State University
Michael Mahoney	Jet Propulsion Laboratory
Greg McFarquhar	University of Illinois Urbana-Champaign
Robert Meneghini	NASA Goddard Space Flight Center
John Molinari	University at Albany/State University of New York
Robert Rogers	NOAA Atlantic Oceanographic and Meteorological Laboratory
Karen Rosenlof	NOAA Aeronomy Laboratory
Wayne Schubert	Colorado State University
Henry Selkirk	NASA Ames Research Center
Chris Snyder	National Center for Atmospheric Research
Francis Turk	Naval Research Laboratory
Christopher Velden	University of Wisconsin Madison
Da-Lin Zhang	University of Maryland, College Park
Edward Zipser	University of Utah

Table 2 TCSP Science Missions

Date	Aircraft	Mission Description
July 2	ER-2 (1 flight)	MCS/Deep Convection - Caribbean
July 5-9	ER-2 (3 flights); P-3 (2 flights)	Dennis TD-to-TS-to-Cat 1; Cat 3
July 14-16	ER-2 (2 flights); P-3 (5 flights)	Eastern Pacific Pre-Genesis
July 17	ER-2 (1 flight)	Emily Cat 4
July 20	ER-2 (1 flight)	MCS/Deep Convection - Nicaragua
July 23-25	ER-2 (3 flights); P-3 (4 flights)	Gert wave-to-TD-to-TS-to-landfall
July 27	ER-2 (1 flight)	MCS/Deep Convection - Panama

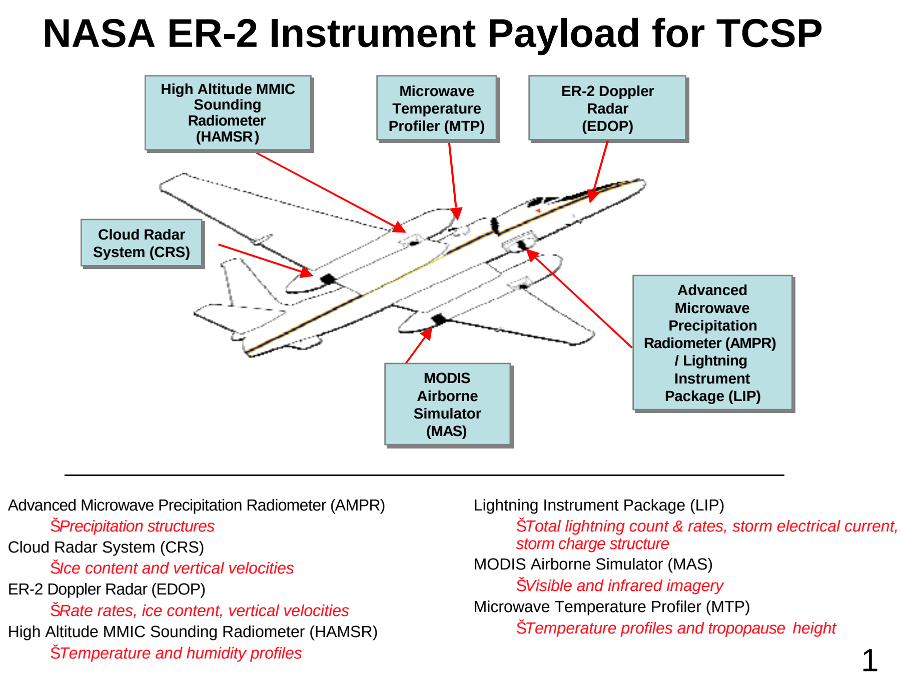


Figure 1. Scientific instrumentation flown on board the NASA ER-2 aircraft during TCSP.

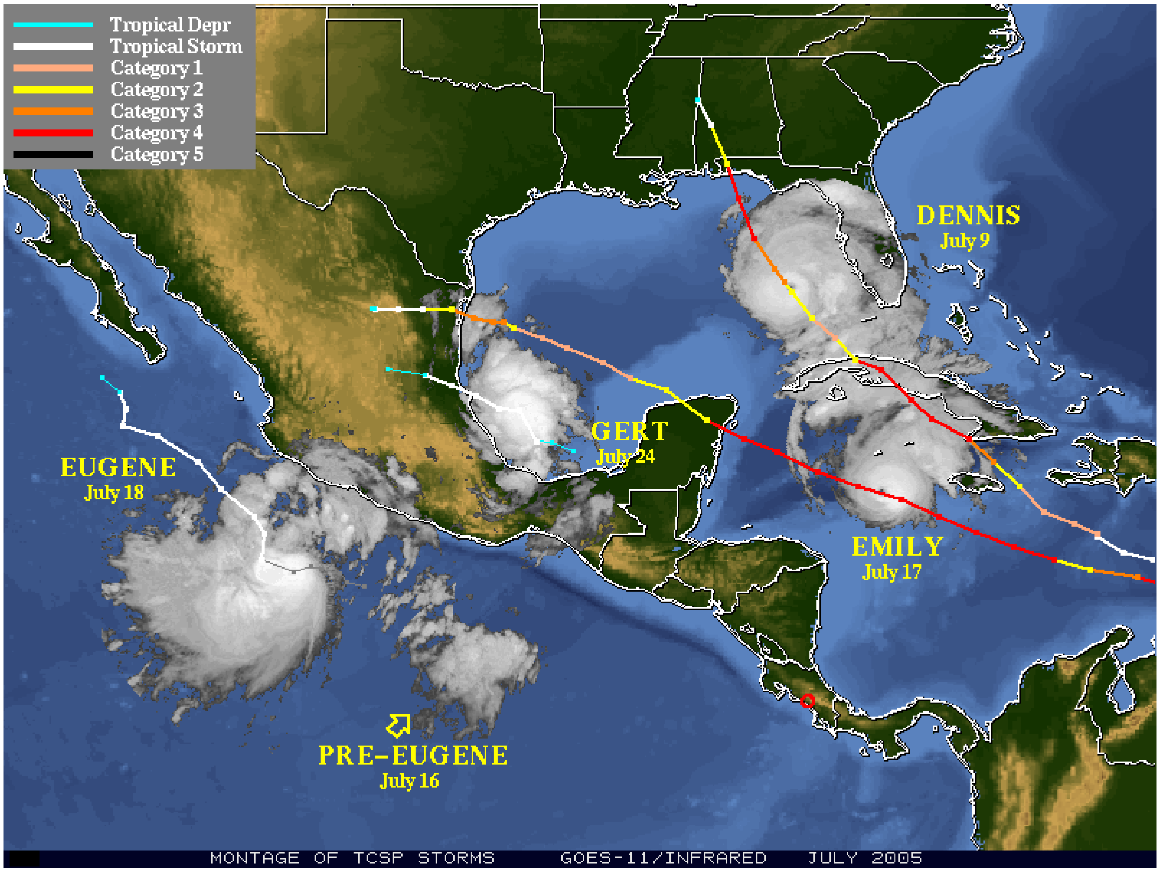


Figure 2. Satellite mosaic showing the principal storms investigated by NASA and NOAA aircraft during TCSP. Track and intensity for each storm are also shown.

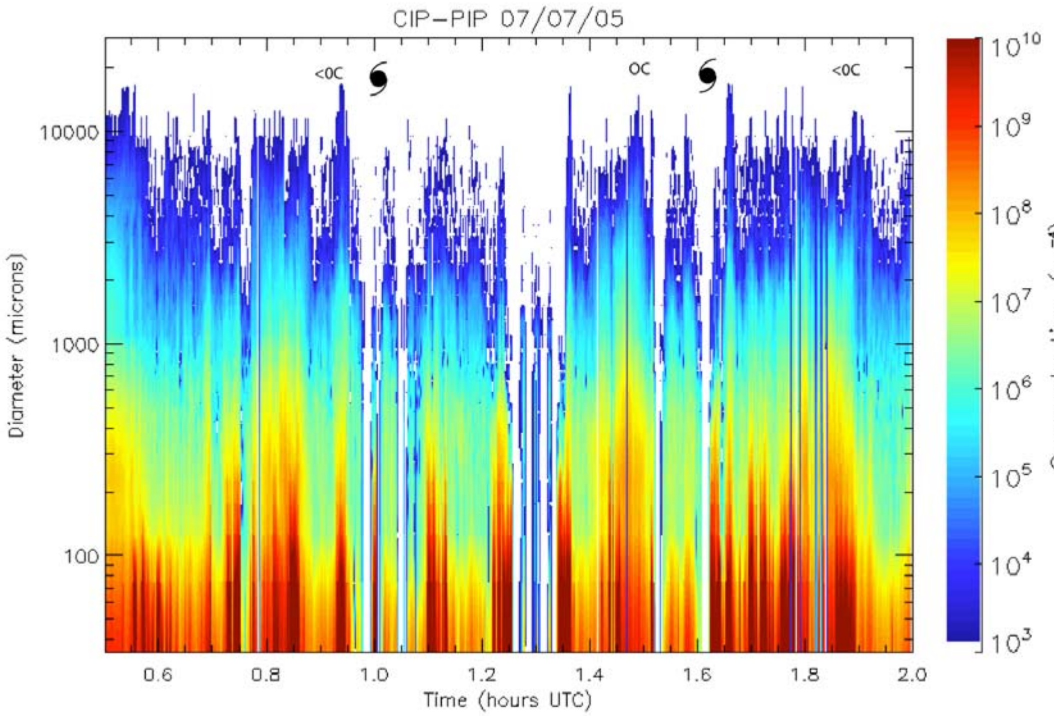
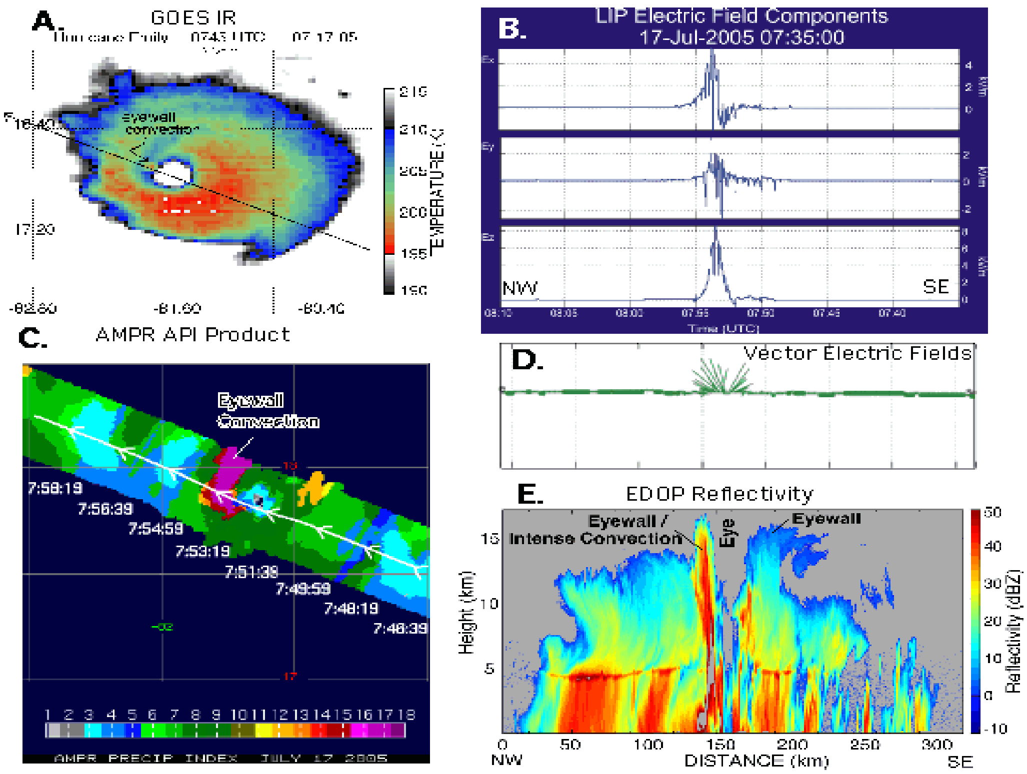


Figure 3: Particle size distribution measurements during two NOAA P3 penetrations through the eye of Hurricane Dennis. The hurricane symbols show the locations of the eye. The color-coding shows representations of the particle size distributions, with an average size distribution plotted over 5-sec intervals along the time (abscissa) axis. Concentrations are color-coded as a function of diameter (ordinate) according to color chart shown.

Figure 4. Pass across the eyewall of Hurricane Emily on 17 July 2005. Shown are a) enhanced IR GOES image with ER-2 flight track, b) LIP component electric field products, c) AMPR API product, d) LIP vector electric field, and e) EDOP reflectivity cross section. Panels (b), (d), and (e) are NW to SE time plots with time decreasing toward the right. For b) the components of the electric field are in aircraft coordinates (Ex =nose to tail, Ey = wing to wing, Ez = up to down). The various discontinuities in the fields are due to lightning flashes in the eyewall. For (c) darker shades of green indicate increasing rain rates with some precipitation ice aloft, while orange, red, and purple shades indicate increasingly large / abundant ice due to scattering in AMPR's lower frequency channels. For (d) the horizontal line is the aircraft track at altitude (nominally, 20 km); green barbs are a representation of the vector electric field along the aircraft track. The length of the barbs is proportional to the magnitude of the electric field while the angle of the barb represents the direction of the electric field.



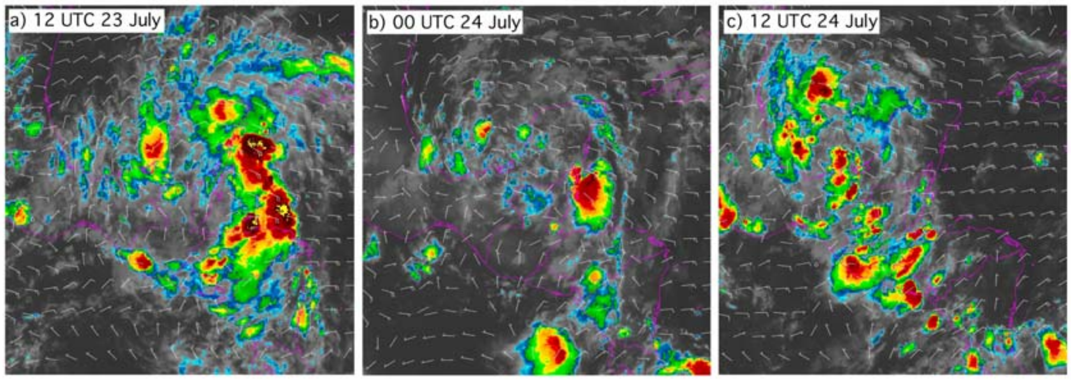


Figure 5. The 1000 hPa winds from NCEP global analyses show the broad scale wave clearly at 0000 UTC 23 July (panel a) as well as two primary regions of convection on each side of the Yucatan peninsula. The only circulation center is found east of the peninsula. By 1200 UTC 23 July (panel b), two distinct circulation centers are present. The eastern center has fallen well behind the wave axis and subsequently weakens. The second circulation center is near the wave axis in the far southern Gulf of Mexico and is also associated with active but not widespread convection. This is the region in which Gert formed. These two images show the complexity that arises as the wave crosses from water to land and back to water. The final image (0000 UTC 24 July, panel c) shows that only one circulation center remains, in the southwestern Gulf, with significant convection occurring within it. Vorticity fields from the NCEP analyses confirm that the center is broad and, like the convection, not clearly focused. The 12 hours before and after this time are most interesting for the diagnosis of how this storm forms within the easterly wave.

Figure 6. A comparison of satellite remotely sensed rainfall and that from a numerical model simulation of Gert. (a) TRMM derived rainfall rates at 1435 UTC 24 July and (b) simulated radar reflectivity and winds at 0.5 km at 1400 UTC from a 2-km grid scale simulation using the WRF model.